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Exploratory Investigations of Low Charpy-V Upper Shelf Energy Steels With Irradiation

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20. Abstract (Continued)

exhibited a high C_v energy correlation (>135 J, 100 ft · lb) at the drop-weight nil-ductility transition (NDT) temperature. Standard C_v and fatigue-precracked C_v specimens were employed for notch ductility and dynamic fracture toughness (K_J) determinations, respectively.

The studies indicated: (1) approximately equal radiation effects to longitudinal and tranverse test orientations for the plate, (2) a significantly lower C_v upper-shelf level for the HAZ compared to the parent plate, (3) greater radiation sensitivity by the HAZ compared to the parent plate as evidenced by transition-temperature elevation, (4) a postirradiation upper-shelf energy for the weld below the code index value of 68 J (50 ft·lb) minimum, and (5) a trend in fracture toughness versus C_v upper-shelf energy suggestive of a correspondence in these properties. For the forging, postirradiation results were inconclusive but revealed the potential for a greater elevation in drop-weight NDT than would be predicted from the radiation-induced elevation in the C_v 68-J transition temperature.

Limited data describing notch ductility recovery by postirradiation heat treatment are presented for one weld material.

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EXPLORATORY INVESTIGATIONS OF LOW CHARPY-V UPPER SHELF ENERGY STEELS WITH IRRADIATION

INTRODUCTION

The detrimental effect of neutron radiation on Charpy-V (C_v) notch ductility is well established for low-alloy steels. The effect is evident as a decrease in specimen energy absorption at upper-shelf temperatures and as an increase in the ductile-to-brittle transition temperature. In the case of nuclear power reactors, the steel plates (or forgings) and welds forming the pressure vessel must exhibit a minimum C_v upper-shelf energy of 68 J (50 ft·lb) to satisfy the ASME Code (Section III) and the Code of Federal Regulations (10CFR50). For current reactor vessel construction, there is little concern over meeting this requirement throughout projected service lifetimes. Older reactor vessel steels, on the other hand, did not have the benefit of current technology for improved radiation resistance, and in addition, generally provide a smaller margin for radiation-induced changes; that is, notch ductility reserve above code minimums.

A series of investigations on low upper-shelf steel plates and welds has been undertaken by the Naval Research Laboratory (NRL) to gain a better understanding of their notch ductility behavior with irradiation. Concurrently, the postirradiation notch toughness of forgings typical of older steel production is being studied to develop important trend information. This report describes exploratory investigations focusing on five questions: (1) the relative effect of radiation on notch ductility in longitudinal (LT, strong) versus transverse (TL, weak) test orientations for plates having highly directional properties as well as a low upper shelf in the TL orientaion, (2) the properties of the heat-affected zone (HAZ) produced in low upper-shelf plates by welding, (3) the effect of radiation on the HAZ compared to base metal of low upper-shelf plates, (4) the significance of radiation-induced degradation of upper-shelf energy of forgings having a high (>135-J, 100 ft·lb) C_v energy correlation at the drop-weight nil-ductility transition (NDT) temperature before irradiation, and (5) the correlation of postirradiation C_v notch ductility and dynamic fracture toughness trends for low upper-shelf weldments.

Few data exist on HAZ properties for low upper-shelf steels for either as-welded or irradiated conditions. Currently there is concern as to whether or not welding produces a HAZ having a poorer upper-shelf level than the base material. Similarly, few data have been obtained for the irradiation behavior of reactor-vessel forgings. For forgings of the type studied, an important question is whether or not radiation can cause a change in NDT correspondence with the C_v energy curve from the transition regime to the upper-shelf regime, or alternatively, whether or not radiation can cause a reduction in the C_v energy index for NDT. The exploratory investigations reported here include comparisions of notch ductility and dynamic fracture toughness (K_J) determined with standard and fatigue-precracked C_v specimens, respectively.

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MATERIALS

Materials selected for the investigation are identified by chemical composition and heat treatment in Table 1. Except for the HAZ, all materials were produced commercially. Purchase specifications for the plate [1] were intended to maximize the difference in plate directional properties; that is, the specifications called for the use of a minimum of cross rolling in the processing of the ingot and slab to plate. Heat-treatment conditions were patterned after typical heat-treatment conditions for old-production A302-B steel [1]. This plate also served as the source of material for the HAZ specimen blanks.

Table 1 — Chemical Composition and Heat Treatment of Plate, Weld, and Forging

Material	Thickness		Chemical Composition (Wt-%)									Drop-Wt. NDT		Heat Treatment*
	cm	in.	C	Mn	P	S	Si	Ni	Cr	Mo	Cu	°C	°F	
A302-B Plate†	15	6	0.21	1.46	0.010	0.021	0.24	0.23	0.06	0.54	0.059	-23	-10	1
A533-B Weld‡ (Code W)	23	9	0.09	1.45	0.020	0.013	0.68	0.57	0.06	0.39	0.35	¶	¶	2
A508-2 Forging‡ (Code Q89)	17	6.5	0.16	0.59	0.011	0.010	0.28	0.69	0.36	0.62	0.11	-12	10	3

*1. Austenitized: 885° to 913°C (1625° to 1675°F) for 1 hour per inch minimum; water quenched; tempered 660°C (1220°F) for 1 hour per inch minimum; water quenched; stress-relief annealed at $612^\circ C^{+14^\circ C}_{-28^\circ C}$ $(1150^\circ F^{+25^\circ F}_{-50^\circ F})$ for 32 hours; furnace cooled to below 316°C (600°F).
2. Postweld heat treatment: 593° to 621°C (1100° to 1150°F) for 24 hours, furnace cooled.
3. Austenitized: 857°C (1575°F) for 5 hours, water quenched; tempered 649°C (1200°F) for 6.25 hours; furnace cooled to 316°C (600°F); stress-relief annealed at 621°C (1150°F) for 30 hours; furnace cooled to 316°C (600°F).

†Source material for HAZ simulation.
‡Composition courtesy supplier.
¶Not available.

HAZ specimen blanks were removed from the plate at the one quarter-thickness (1/4T) location in the TL orientation. The HAZ was produced by weld simulation using a Gleeble apparatus. The weld thermal cycle simulated high-heat-input (submerged-arc) welding of a 10.2-cm(4-in.)-thick plate of carbon steel at 177°C (350°F) preheat. The peak temperature of the thermal cycle was 1316°C (2400°F). A 32-hour 621°C (1150°F) stress-relief anneal was applied following the welding simulation.

Plate and forging specimens for radiation testing were also taken from the quarter-thickness locations. Plate specimens were taken in LT and TL orientations; the forging specimens were taken in the LT orientation only. For the weld, specimens were removed at all locations through the thickness except for the surfaces. The long axis of the specimen was perpendicular to the welding direction; the direction of crack propagation was made parallel to the weld length.

FRACTURE TOUGHNESS (K_J) TESTING

The C_v specimens for K_J determinations were fatigue precracked at 24°C (75°F) before irradiation. Precracking was accomplished on a Saytec Model SF-1U fatigue tester (1800 cpm). The specimen crack length-to-width ratio (a/W) was 0.5 (aim); the maximum stress intensity during precracking (K_f max) was less than 22 MPa$\sqrt{m}$ (20ksi$\sqrt{in.}$).

Precracked (PC) specimen testing was in accordance with EPRI procedures for measuring fracture toughness [2]. Values of K_J were determined by the J-integral method and were based on energy absorbed to maximum load, corrected for specimen and machine compliance. In this regard, it is recognized that J-integral determinations based on maximum load imply the absence of stable (rising load) crack extension. This is normally not the case for K_J determinations at upper shelf temperatures for the type of specimen employed.

MATERIAL IRRADIATION

The materials were irradiated at 288°C (550°F) in the University of Buffalo Reactor (UBR) B-4 fuel lattice position. Irradiation temperatures were controlled externally and were monitored continuously by means of multiple thermocouples in each specimen array. Neutron fluences received by individual materials ranged from 2.3×10^{19} to 2.6×10^{19}n/cm^2 > 1 MeV (calculated neutron spectrum) and depended on the experiment subsection involved. Fluences were based on measurements with iron neutron dosimeter wires included in each specimen array. The irradiation period was approximately 800 hours.

EXPERIMENTAL RESULTS: HAZ SIMULATION

The C_v data for the HAZ simulation are compared to data trends for the unwelded plate in Fig. 1 (see also Fig. 3, upper graph). Significantly, the HAZ shows a 25-percent lower C_v upper-shelf level than the parent plate at the same quarter-thickness location and orientation (49 J, 36 ft·lb versus 65 J, 48 ft·lb). The present concern over the effect of welding on C_v upper-shelf properties for the case of low upper-shelf plates thus appears justified. In Fig. 1, a lowering of the C_v 41-J (30 ft·lb) transition temperature is also noted for the weld simulation. This beneficial change, however, is masked by the degradation in upper-shelf level.

Dynamic fracture toughness assessments of the HAZ similarly revealed a degradation of plate upper-shelf properties with the weld simulation. Duplicate K_J tests at 93°C (200°F), corresponding to the upper-shelf regime, gave values of 129 and 130 MPa$\sqrt{m}$ (117 and 118 ksi$\sqrt{in.}$) for the HAZ, whereas K_J values for the parent plate at about the same temperature averaged 213 MPa$\sqrt{m}$ (194ksi$\sqrt{in.}$).

EXPERIMENTAL RESULTS: IRRADIATED CONDITION

A302-B Plate

Postirradiation C_v results for LT vs TL orientations of the plate are given in Fig. 2. To conserve the material stock, specimens for this comparison were taken from the 3/4T location in the plate while HAZ specimens (blanks) for irradiation were taken from the adjoining 1/4T

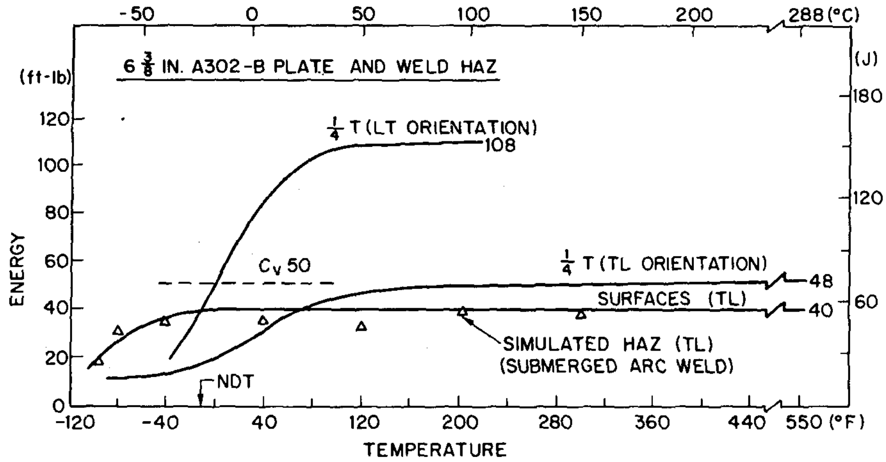

Fig. 1 — Charpy-V notch ductility of the simulated-weld HAZ (open triangles) compared with the A302-B parent plate (curves). HAZ specimen blanks were removed from the plate quarter-thickness location in the transverse (TL) test orientation. Trend curves for the plate surface location (TL) and for the quarter-thickness location (LT orientation) are also shown for reference.

location. Differences in C_v properties between the two locations are seen to be negligible with regard to upper-shelf level and small with regard to transition behavior. Three primary observations can be made from Fig. 2. First, high radiation resistance is indicated by both test orientations. Secondly, the effect of radiation on upper-shelf level appears to be the same for each orientation; the effect of radiation on transition temperature is also comparable between orientations. Thirdly, it is observed that radiation can induce a measurable transition-temperature elevation without reducing upper-shelf energy level.

Large radiation-induced changes in notch ductility were not expected for this particular plate because of its low copper and phosphorus content. In fact, it was selected for study partially for the opportunity to demonstrate, for commercial production A302-B, improved radiation resistance through the restriction of copper and phosphorus impurities. The results clearly show this improvement. Reference 3 documents a forerunner demonstration test for A533-B steel, representing a steel of current vessel manufacture.

Unlike the C_v energy results, K_J determinations indicated a reduction in upper-shelf toughness with irradiation (Table 2). The average K_J for the TL orientation, for example, was reduced from 213 MPa$\sqrt{m}$ (194ksi$\sqrt{in.}$) to 152 MPa$\sqrt{m}$ (138ksi$\sqrt{in.}$). A parallel reduction in K_J for the LT orientation is implied by the data for the LT orientation (irradiated condition) and the TL orientation (unirradiated condition). An explanation for the inconsistency in upper-shelf C_v energy versus K_J indications cannot be tendered at this time; however, one possibility is that a change in stable crack extension before maximum load by irradiation is responsible.

Heat-Affected Zone

Figure 3 summarizes C_v results obtained for the HAZ. The upper graph compares unirradiated-condition HAZ data to reference data for the parent plate at the same testing location (1/4T); the lower graph compares HAZ preirradiation and postirradiation performance.

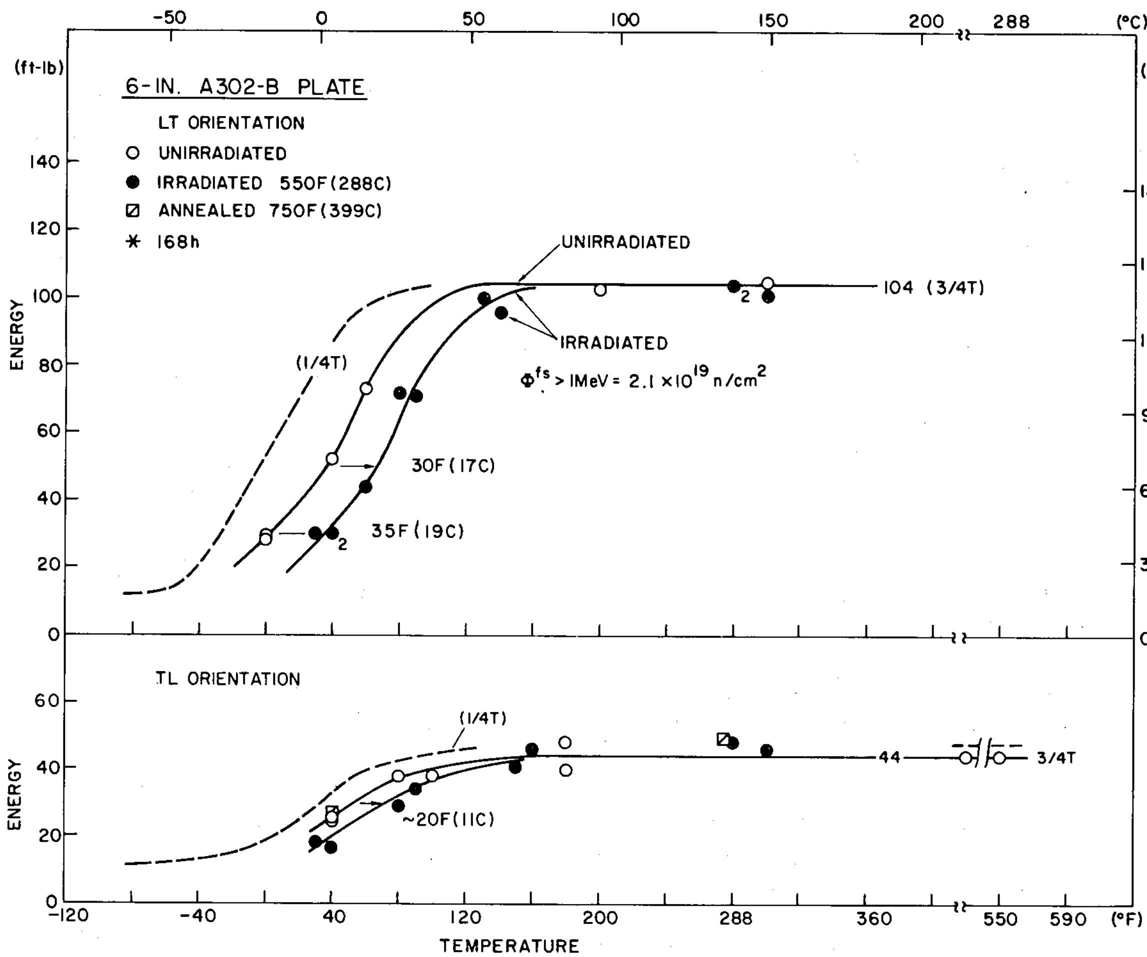

Fig. 2 — Charpy-V notch ductility of the A302-B plate in longitudinal (upper graph) and transverse (lower graph) test orientations before and after 288°C irradiation. A datum for the 399°C (750°F) postirradiation heat-treated condition is also shown. The dashed curves describe the performance of the plate 1/4T location from which the HAZ specimens (see Fig. 3) were taken.

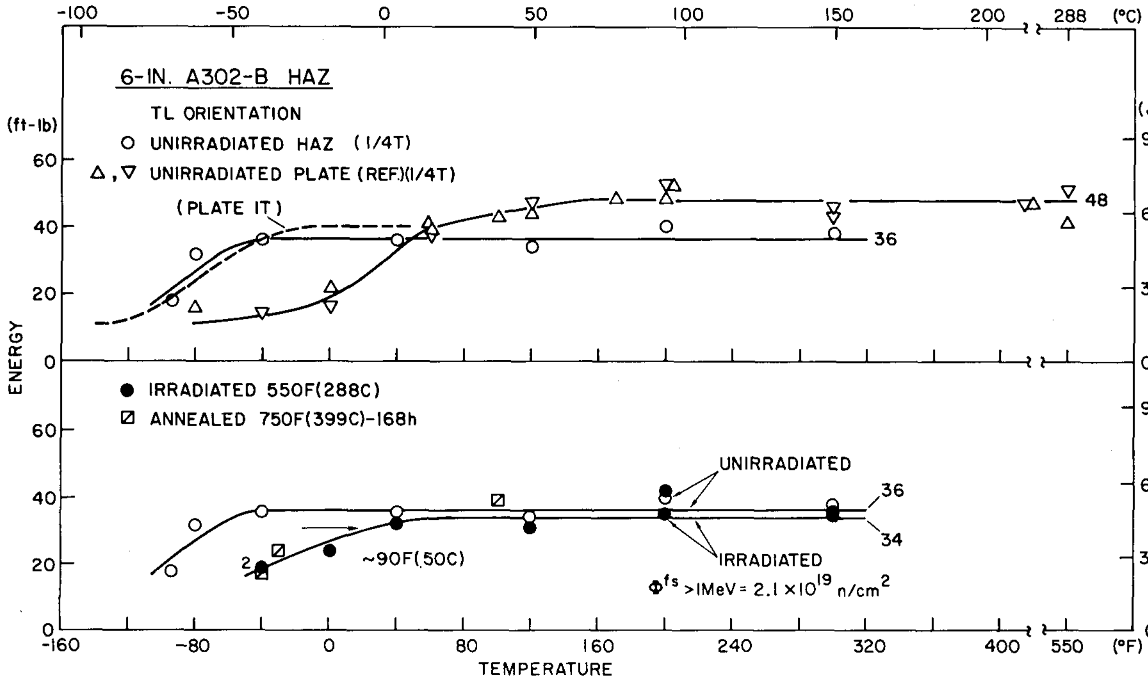

Fig. 3 — Charpy-V notch ductility of the simulated-weld HAZ in the transverse test orientation. The upper graph shows data for the HAZ relative to that of the parent plate at the same (1/4T) test location. The lower graph compares the properties of the HAZ before and after irradiation.

Overall, the HAZ shows good radiation resistance, especially with regard to upper-shelf energy retention. From Fig. 3 and Fig. 2, however, it will be noted that the HAZ appears much more sensitive to radiation than the parent plate from the standpoint of transition temperature elevation. It is also noted that, for this particular radiation exposure, the HAZ transition temperature was not elevated above that of the parent plate. Whether or not this relationship holds for higher fluences or for plate and HAZ materials with higher radiation sensitivities (higher impurity copper contents) is not known.

Only a single determination of fracture toughness was obtained for the HAZ (Table 2), although several PCC_v specimens were irradiated. The datum suggests that irradiation did not lower the K_J of the HAZ; the value falls within the expected range of data scatter for the preirradiation condition. This contrasts to the reduction in K_J with irradiation found for the parent plate.

Submerged-Arc Weld

Data developed for the A533-B weld are given in Fig. 4. Referring to the unirradiated condition, the large open circles represent NRL check test data and the small open circles indicate vendor data. In view of the general agreement of the data, the transition curve based on vendor data was used in calculating the transition-temperature elevation by irradiation.

Several observations are permitted by the results: (1) The weld upper-shelf level was reduced below the code C_v energy index of 68 J (50 ft·lb) minimum. (2) The upper-shelf energy reduction (ΔE) is about equal to that measured at a lower fluence of 7.3×10^{18}n/cm^2 > 1

Table 2 — Postirradiation Fracture Toughness (K_J) of Plate, HAZ, Weld, and Forging

Material	Temp. (°C)	K_J (Irrad.)		Average K_J (Irrad.) (MPa$\sqrt{m}$)	Average K_J (Unirrad.) (MPa$\sqrt{m}$)
		MPa$\sqrt{m}$	ksi$\sqrt{in.}$		
Plate (LT)	143	185 192	168 175	189	*
Plate (TL)	93 143	156 141 158	142 128 144	152	213
HAZ	93	143	130	143†	130
Weld	177	129 136	117 124	133	*
Forging	-12 77	* 203 208	* 185 189	* 206	156‡ *

*Not available.
†Single value.
‡K_J range: 64 to 220 MPa$\sqrt{m}$ (58 to 200 ksi$\sqrt{in.}$).

MeV for a different section of the weld* [4]. The respective transition-temperature elevations for the two fluences, on the other hand, differ appreciably: 131°C (235°F) vs 89°C (160°F). (3) The observed radiation changes are consistent with projections of radiation effects (conservative) of Nuclear Regulatory Commission Guide 1.99 [5]. For example, the upper-shelf reduction of 39 percent compares favorably with the Guide projection of 46 percent. The Guide projection for the lower fluence experiment, by comparison, was 40 percent.

Table 2 reports an average K_J of 133 MPa$\sqrt{m}$ (121ksi$\sqrt{in.}$) for the postirradiation upper-shelf condition. For static testing, Rolfe and Novak [6] observed a correspondence between K_{Ic} and C_v upper-shelf energy given by the empirical relationship

$$\left(\frac{K_{Ic}}{\sigma_y}\right)^2 = 5\left(\frac{CVN}{\sigma_y} - 0.05\right).$$

The substitution of the measured weld dynamic yield strength for σ_y in the formula provides an estimate of K_J (145 MPa$\sqrt{m}$) that is close to the measured K_J value. It was further noted that the magnitude of K_J (MPa$\sqrt{m}$) relative to C_v energy level (J) for the weld (133 vs 57) agrees quite well with that observed for the HAZ before irradiation (130 vs 49) and that observed for the TL orientation of the plate after irradiation (152 vs 60). An exception to this trend is found in the values for the TL orientation in the unirradiated condition (213 vs 60). This inconsistency bears further investigation, as stated above.

*The preirradiation upper-shelf level of this weld section was 104 J (77 ft · lb).

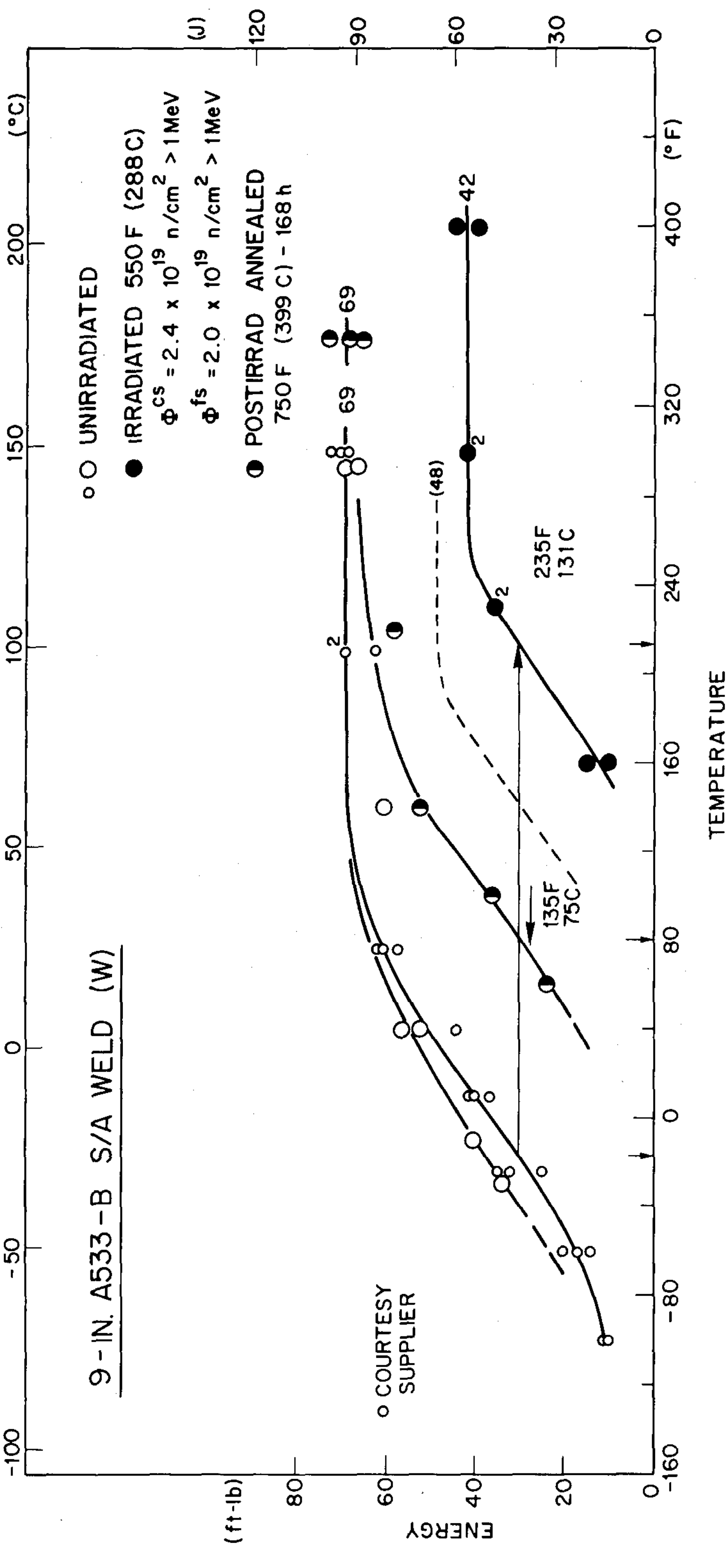

Fig. 4 — Charpy-V notch ductility of the A533-B submerged arc weld deposit after irradiation and after postirradiation heat treatment. Irradiation is seen to reduce the upper-shelf energy level to below the code index value of 68 J (50 ft · lb) minimum; however, full upper-shelf recovery was obtained by heat treating.

Figure 4 also presents data on the weld response to a 399°C (750°F) postirradiation heat treatment. The heat treatment produced 100-percent recovery in upper-shelf level but only 57-percent recovery in transition temperature. Extensive investigations of postirradiation heat treatment response are underway at NRL. This method is proposed by the codes as one means for periodically reducing radiation effects in service.

A508-2 Forging

Figure 5 illustrates the C_v behavior of the forging. It is recalled that this forging was specially selected because of its high C_v energy correlation at the drop-weight NDT temperature. Consistent with its higher copper content, the forging exhibits a somewhat greater radiation sensitivity than the A302-B plate (Fig. 2). Approximately equal transition-temperature increases are indicated for C_v 41-J (30 ft·lb) and C_v 68-J (50 ft·lb) energy levels. More importantly, radiation is shown to produce a marked change in C_v curve shape above the 136-J (100 ft·lb) level such that the upper-shelf condition is not attained until a temperature of ~150°C (300°F) is reached. In turn, the energy level corresponding to the preirradiation NDT is not developed until a temperature of ~121°C (250°F) is attained.

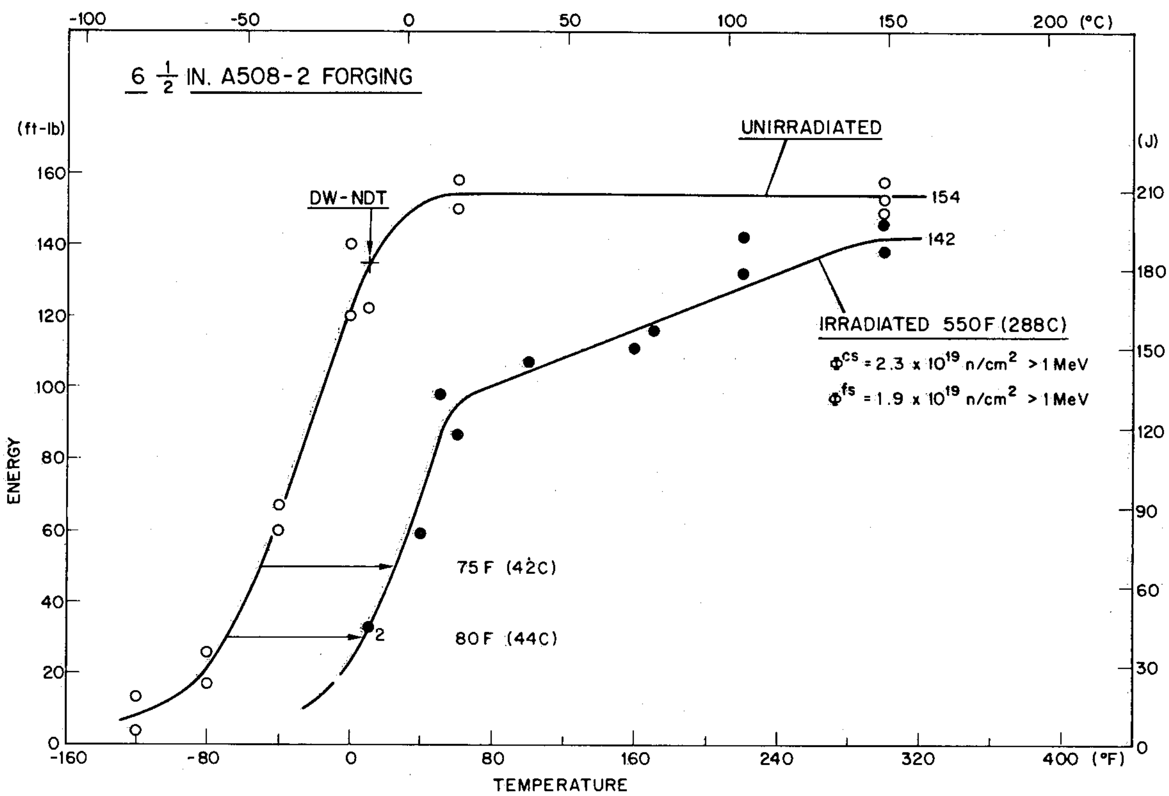

Fig. 5 — Charpy-V notch ductility of the A508-2 forging before and after irradiation. The change in shape of the transition curve with irradiation makes the prediction of postirradiation NDT temperature from the C_v 68-J (50-ft·lb) transition-temperature elevation (conventional method) questionable.

The primary question in this case is the point of NDT development after irradiation. On one hand, the C_v 68-J transition shift suggests an NDT increase of 42°C (75°F). On the other hand, an NDT increase of 133°C (240°F) can be projected on the basis of equivalent C_v energy levels. Some clarification is possible from apparent postirradiation fracture toughness. In Table 2, the observed K_J values suggest that the NDT temperature is not as high as 121°C (250°F) and quite possibly is below 77°C (170°). That is, the average measured K_J at 77°C significantly exceeds that which would be predicted (60 to 66 MPa$\sqrt{m}$) for the NDT. The postirradiation K_J determinations, however, are too few to be conclusive. As noted in Table 2, tests of unirradiated material at the NDT temperature produced a range of K_J values from 65 to 220 MPa$\sqrt{m}$. In this instance, high data scatter would be expected in view of the rapid rise of the C_v energy curve with temperature.

Further investigation of K_J versus C_v energy characteristics for forgings is planned.

CONCLUSIONS

Primary observations and conclusions developed by the investigations are the following:

- High heat-input, submerged-arc welding of low upper-shelf A302-B steel plates has the potential for producing a weld heat-affected zone with a lower C_v upper-shelf energy than the base metal.

- The HAZ produced in low upper-shelf A302-B plate can exhibit greater radiation sensitivity than the parent plate from the standpoint of transition temperature elevation. However, comparably high radiation resistance relative to upper-shelf energy retention was observed between the simulated weld HAZ and its A302-B parent plate (low copper and phosphorus content).

- The postirradiation transition temperature of the HAZ was lower than the postirradiation transition temperature of the parent plate after 2.1×10^{19}n/cm^2 > 1 MeV, thereby offsetting the higher radiation sensitivity of the HAZ (see preceding observation).

- Equally high radiation resistance was found for the LT and TL orientations of the A302-B plate. Additionally, the plate provided a successful demonstration for A302-B of improved radiation resistance through limitations on copper and phosphorus impurities.

- A significant elevation in transition temperature can be induced by radiation without an accompanying reduction in upper-shelf energy level.

- Values of dynamic fracture toughness (K_J) determined for C_v upper-shelf energies of 49, 57, and 60 J (36, 42, and 44 ft·lb) were equal to or greater than 130 MPa$\sqrt{m}$ (118 ksi$\sqrt{in.}$).

- Nuclear Regulatory Commission Guide 1.99 predicted well the observed radiation-induced change in notch ductility of a 0.35% copper content submerged-arc weld.

- A large (3:1) difference in predicted drop-weight NDT temperature elevation by irradiation was observed between a prediction based on the C_v 68-J (50-ft lb) transition-temperature elevation and a prediction based on the elevation in temperature of the C_v:NDT energy-index point. This inconsistency is seen to have an important bearing on projections of the reference nil-ductility transition temperature (RT_{NDT}) for forgings by ASME Code procedures.

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